Scintillator avalanche photoconductor with high resolution emitter readout for low dose x-ray imaging: Lag

Dan Li^{a)} and Wei Zhao

Department of Radiology, State University of New York at Stony Brook, L-4 120 Health Science Center,
Stony Brook, New York 11794-8460

Masakazu Nanba and Norifumi Egami

Science and Technical Research Laboratories, Japan Broadcasting Corporation, 1-10-11 Kinuta,
Setagaya-ku, Tokyo, 157-8510 Japan

(Received 18 February 2009; revised 6 June 2009; accepted for publication 7 July 2009;
published 12 August 2009)

Purpose: A new concept of indirect conversion flat-panel imager with avalanche gain and field emitter array (FEA) readout is being investigated. It is referred to as scintillator avalanche photoconductor with high resolution emitter readout (SAPHIRE). The present work investigates the temporal performance, i.e., lag, of SAPHIRE.

Methods: Since the temporal performance of the x-ray detection materials, i.e., the structured scintillator and avalanche amorphous selenium (*a*-Se) photoconductor, has been studied previously, the investigation is focused on lag due to the FEA readout method. The principle of FEA readout is similar to that of scanning electron beam readout used in camera tubes, where the dominant source of lag is the energy spread of electrons. Since the principles of emission and beam focusing methods for FEA are different from thermionic emission used in camera tubes, its electron beam energy spread and hence lag is expected to be different. In the present work, the energy spread of the electrons emitted from a FEA was investigated theoretically by analyzing different contributing factors due to the FEA design and operations: The inherent energy spread of field emission, the FEA driving pulse delay, and the angular distribution of emitted electrons. The electron energy spread determined the beam acceptance characteristic curve of the photoconductive target, i.e., the accepted beam current (I_a) as a function of target potential (V_t), from which lag could be calculated numerically. Lag calculation was performed using FEA parameters of two prototype HARP-FEA image sensors, and the results were compared with experimental measurements. Strategies for reducing lag in SAPHIRE were proposed and analyzed.

Results: The theoretical analysis shows that the dominant factor for lag is the angular distribution of electrons emitted from the FEA. The first frame lags for two prototype sensors with 4 and 25 μm HARP layer thicknesses were 62.1% and 9.1%, respectively. A lag clearance procedure can be implemented by turning on all the FEA pixels simultaneously between subsequent frames without negative impact of readout speed. For large-area SAPHIRE, the bias electrode for the HARP needs to be divided into strips to allow parallel readout. With typical cardiac detector parameters, SAPHIRE with 128 parallel strips can provide real-time readout (30 frames/s) with first frame lag of $\sim 4\%$.

Conclusions: The investigation of lag in SAPHIRE shows that the angular distribution of emitted electrons from FEA can result in substantial lag if the readout was performed pixel by pixel. Effective strategies for reducing lag include dividing the bias electrode into multiple strips to allow parallel readout and the incorporation of rapid charge clearance procedure between subsequent frames or rows. © 2009 American Association of Physicists in Medicine.

[DOI: [10.1118/1.3187227](https://doi.org/10.1118/1.3187227)]

Key words: flat-panel detector, indirect detection, cesium iodide, amorphous selenium, avalanche gain, field emitter array, high resolution, x-ray imaging, fluoroscopy

I. INTRODUCTION

A new concept of indirect conversion flat-panel imager (FPI) with avalanche gain and field emitter array (FEA) readout is being investigated,¹ which is referred to as scintillator avalanche photoconductor with high resolution emitter readout (SAPHIRE). The structure is shown schematically in Fig. 1. It is made by optically coupling (e.g., through fiber optics) a thallium (Tl) doped needle-structured cesium iodide (CsI)

scintillator to a uniform thin layer (4–25 μm) of avalanche amorphous selenium (*a*-Se) photoconductor called high-gain avalanche rushing amorphous photoconductor (HARP). The optical photons emitted by the CsI scintillator upon x-ray absorption transmit through a transparent indium tin oxide (ITO) bias electrode of HARP and generate electron-hole pairs near the entrance surface of the HARP layer. Under a positive bias potential applied to the ITO electrode through a

FIG. 1. Schematics showing the concept of the proposed detector SAPHIRE: (a) 3D structure of the main components of the detector; (b) cross-sectional view showing the operating principles.

resistor, the holes move toward the bottom free surface of the HARP and experience a programmable avalanche multiplication under an electric field of $E_{Se} > 80 \text{ V}/\mu\text{m}$.²⁻⁵ An amplified image is formed at the bottom surface of HARP and readout by the electron beams generated from a two-dimensional (2D) FEA, which is placed at a short distance, e.g., 1–2 mm, below the scintillator-HARP (SHARP) structure. Each pixel of FEA contains multiple Spindt-type field emitter (FE) tips, made by molybdenum (Mo).^{6,7} When a positive potential (e.g., 40–100 V) is applied between the gate and base electrode, the pixel defined by the crossing over area of gate and base electrode will be turned on and the electrons are emitted. A mesh electrode with positive potential (e.g., 300 V or higher) is inserted halfway between the FEA and HARP target to minimize the lateral spread of electron beams. The amount of charge required to neutralize the hole image is read out by an amplifier connected (through ac coupling) to the ITO electrode and form the output signal. This detector is designed to improve its low dose performance with a better resolution. By varying the avalanche gain, it can overcome the electronic noise and enhance the detective quantum efficiency (DQE) to the theoretical limit for both R/F and mammographic imaging applications, i.e.,

x-ray quantum noise limited performance and a wide dynamic range can be obtained.⁵ It is important to note that the feasibility of using a thin film transistor (TFT) array to read out the charge image formed by SHARP is also being investigated.^{1,8} However, SAPHIRE using FEA readout has the following practical advantages over the TFT readout method:⁹ (1) Higher radiation resistance because FEA has no radiation sensitive components; (2) the deposition procedure of the HARP multilayer structure is identical to that in the well-established HARP tube device;^{7,10} and (3) the free surface of the HARP layer provides a self-protection mechanism for faulty detector conditions leading to excessive signal current, whereas additional protection mechanism is required in the TFT readout method to prevent damage due to high signal current.

Previously we have investigated the spatial resolution of SAPHIRE.² The focus of this present investigation is its temporal performance. The temporal performance of an x-ray imaging detector is usually characterized by lag and ghosting, which measure the residual signal and change in sensitivity from previous x-ray exposures of the detector, respectively.¹¹ Three major detector components of SAPHIRE could contribute to the lag and ghosting, which are (1) the structured scintillator for x-ray detection, (2) HARP layer for optical photon detection, and (3) the FEA readout method. In a fluoroscopic system, lag is usually required to be less than 10% after the first frame,¹² and the values measured from most indirect active matrix FPIs (AMFPIs) are between 2% and 10% depending on the x-ray exposure and detector operation.¹³⁻¹⁵ The temporal performance of CsI (Tl) has been studied extensively for indirect AMFPI. It was found that the lag due to the afterglow of the CsI (Tl) is $\sim 0.1\%$ after 5 ms, and the typical values of ghosting are 1% and 3% at the exposure levels of 1 and 10 mGy, respectively.¹⁶ Therefore the lag in existing indirect AMFPI, which varies between 2% and 10% after the first frame, is dominated by the charge trapping and detrapping in *a*-Si photodiodes. The lag and ghosting in *a*-Se photoconductor exposed to optical photons depend on the density and the depth of the charge traps. We will provide a brief analysis in Sec. II to show that its contribution to lag and ghosting of SAPHIRE is negligible. Therefore our study is focused on the temporal properties associated with the FEA readout method. The FEA is expected to introduce readout lag in SAPHIRE.

FEA has been widely used in display devices and shown advantages in high emission current and low operating voltages.¹⁷ However, there has been very few studies on its fundamental properties related to imaging devices. The principle of FEA readout is similar to the scanning electron beam readout method used in camera tubes (e.g., Vidicon, Saticon) except for the following two differences: (1) Cold source based on field emission as opposed to thermionic emission used in an electron gun of a camera tube; (2) separate electron source for each pixel that is electronically scanned versus the electromagnetically scanned single electron beam in a camera tube. It has been established in the studies of camera tubes that the main mechanism for lag due to the electron

beam readout is the incomplete readout of the image charge on the target surface. During the readout, the target potential V_t decreases as the positive image charges (holes) are neutralized by the electron beam landing on the target. This causes a subsequent decrease in the readout beam intensity because an increasing fraction of the electrons do not have sufficient kinetic energy to reach the target. This phenomenon is responsible for incomplete readout of image charge and is often referred to as the beam discharge lag. It depends on the energy spread of the electron beam, the capacitance of the photoconductive target, and the input signal current.¹⁸ While the target capacitance and the signal current of a HARP-FEA sensor are essentially identical to its camera tube counterpart, i.e., HARP tube, the energy spread of the electron beam is expected to be different due to the difference in emission mechanism and operating scheme. The wider the energy distribution of the electron beam, the higher the lag.

In the present work, we have identified the following factors of the FEA design and operation that can contribute to the energy spread of electron beam: (1) Inherent energy spread of emitted electrons, which resulted from the different probabilities of field emission for electrons at different energy levels within the atoms; (2) the delay of driving pulses for the operation of the FEA, which result in uncertainty in the potential applied to each pixel; and (3) the angular distribution of the emitted electrons. In this paper we will provide a description of the physical mechanisms responsible for the electron beam energy spread in FEA and develop a theoretical framework to quantitatively predict energy spread with different FEA designs and operating conditions, and finally these theoretical foundations will be applied to understand experimental measurements from a small-area prototype HARP-FEA sensor. Based on this framework, we will predict the beam discharge lag for SAPHIRE and propose methods to improve its temporal performance.

II. THEORY AND BACKGROUNDS

II.A. Photoconductive lag in HARP

In this section we will present a simple analysis to show that the photoconductive lag in HARP layer is negligible. Photoconductive lag occurs when charge carriers generated in one frame are carried over to and read out in the subsequent frame. This is caused by trapping and detrapping of photogenerated carriers when they move across the thickness of the *a*-Se layer, d_{Se} . As shown in Fig. 1(b), the holes generated by optical photons in HARP undergo avalanche multiplication when they move across the *a*-Se layer. The electrons created upon impact ionization move toward the positive ITO bias electrode. Under an electric field of E_{Se} , the charge transit time T_R is given by^{19,20}

$$T_R = \frac{d_{Se}}{\mu_C E_{Se}}, \quad (1)$$

where μ_C is the drift mobility of charge carriers in *a*-Se. At avalanche field strength ($E_{Se} > 80 \text{ V}/\mu\text{m}$), the mobilities for

FIG. 2. Schematic diagram showing the electron energy levels inside a HARP-FEA image sensor. The thick, black solid lines depict the change in energy of an emitted electron as it traverses from the FE tip to the HARP target. It shows that the electron can only land on the target with sufficiently high target potential (V_{t1}); otherwise (e.g., with V_{t2}) the electron does not have sufficient kinetic energy to travel to the target and will return to the mesh electrode.

electrons and holes are 0.06 and $1.0 \text{ cm}^2/\text{V s}$, respectively.³ The drift mobility accounts for the time a carrier spends in shallow traps, therefore T_R provides the total transit time of a carrier from one bias electrode to the other. For HARP thickness of $d_{Se} = 25 \text{ }\mu\text{m}$, T_R can be calculated from Eq. (1) as $0.04 \text{ }\mu\text{s}$ for electrons and 2.5 ns for holes. These values are much smaller than the frame time ($T_F = 33 \text{ ms}$ for real-time readout); therefore it is reasonable to conclude that photoconductive lag in HARP is negligible.

This is consistent with the experimental findings in HARP image pickup tubes (using scanning electron beams),^{10,21} where lag was dominated by the image readout (beam discharge) lag. A typical lag was 1.2% after 50 ms with a target capacitance of 400 pF and an effective beam temperature of $T = 3000 \text{ K}$.

II.B. Mechanisms of energy spread

In electron beam readout, the amount of image charge read out from each pixel is determined by the integral of the actual beam current accepted by the target (i.e., the signal current I_a) over the pixel readout time (t_p). Although the emission current (I_e) from each FEA pixel is typically $2 \text{ }\mu\text{A}$ or higher to ensure a wide dynamic range, not all the emitted electrons can reach the target to contribute to readout. Shown in Fig. 2 is a schematic diagram depicting the different energy levels an emitted electron possesses when it traverses from the FE tip to the HARP target. When an electron is emitted through tunneling mechanism, its initial energy corresponds to the energy state it occupied within the atom. As the electron travels through the gate and mesh electrodes, it

gains kinetic energies corresponding to the potential differences between the electrodes. After passing the mesh electrode, the electron decelerates since the target potential (V_t), which is usually on the order of tens of volts as a result of optical exposure, is lower than the mesh potential V_m (300–700 V). Only those electrons with sufficient kinetic energy can reach the target after deceleration, and the others will return to and be absorbed by the mesh electrode. As shown in Fig. 2, the electrons can reach the target only if V_t is greater than the initial energy of the electrons. As V_t approaches the initial energy of the electrons, the inherent energy spread of the emitted electrons plays an important role in how efficient the electron beam reads out image charge, i.e., lag.

The energy spread of the emitted electrons is the dominant factor for beam discharge lag.^{18,22–24} There are several contributing factors to the final energy spread: (1) Inherent energy spread due to field emission process, (2) variation in base potential V_b due to the driving pulse delay, and (3) angular distribution of emitted electrons after passing through the gate electrode. The mesh electrode is essentially employed in order to minimize the lateral spread of electrons.^{7,25} It does not increase or decrease the energy spread. Here we will describe the mechanism for each factor separately.

II.B.1. Inherent energy spread

The inherent energy E_i refers to the energy level occupied by an electron inside the FE tip. The probability of field emission through tunneling increases with the energy level of the electron.^{26–29} The probability of an electron occupying a higher energy level follows the Fermi-Dirac distribution, while the tunneling probability is determined by the electric field E_{FE} . For a given FE tip material and operation temperature (room temperature $T=300$ K), the inherent energy spread of emitted electrons is only affected by E_{FE} .

II.B.2. Driving pulse delay

As shown in Fig. 2, when an emitted electron passes the gate electrode, it gains a kinetic energy $E_{bg}=q(V_g-V_b)$ due to the change in potential, where q is the elementary charge. In reality the base potential V_b is not constant during the pixel readout time due to the delay of driving pulses. The FEA is operated with a passive driving scheme, where a potential difference is applied across orthogonal base and gate lines [Fig. 1(a)]. Each pixel is addressed by applying a forward bias between the gate and the base electrode, as shown in Fig. 3. At the beginning of each line, a positive bias is applied to the gate while the base of each pixel is also biased positively so that no field emission occurs. A pixel is turned on by applying 0 V to its corresponding base electrode, resulting in a forward bias between the gate and base. The driving pulse width for each pixel is typically $t_p=160$ nS for an image sensor with 256×192 pixels and 30 frames/s readout rate.²⁵

In a passive driving scheme, the impedance of each gate and base electrode can be represented by a distributed

FIG. 3. Diagrams showing the driving scheme for the FEA: The top two wave forms depict the driving pulses applied to the gate line and base line, respectively, and the bottom wave form shows conceptually the delay of the driving pulses due to the RC load of each base line.

resistance-capacitance (RC) network. The rectangular driving pulse for the base electrode, which constitutes the pixel clock, is delayed as it propagates through the RC load. This base potential delay results in a variation in E_{bg} and hence further energy spread. The electrons emitted with higher V_b will require higher V_t to reach the target. Furthermore, driving pulse delay also results in variation in E_{FE} , which affects the initial energy spread. The driving pulse delay also occurs on the gate line. However, since the gate line bias is applied well before the pixel clocks begin, it would not cause variation in E_{bg} .

II.B.3. Angular distribution

The emitted electrons pass the gate electrode with some kinetic energy (E_g). However, it has been shown both theoretically and experimentally that the electrons are emitted with a wide angular distribution.³⁰ Only the vertical component of kinetic energy, E_z , determines whether an electron can reach the target: $E_z=\frac{1}{2}mv_z^2$, where m is the electron mass and v_z is the vertical component of velocity. The angular distribution of emitted electrons causes further spread in E_z . The effect of angular distribution of electrons on energy spread in camera tubes has been investigated previously.^{18,23} It played a minor role in lag because the incident angle at the last mesh electrode (θ_m) is $<5^\circ$ with a well designed electron beam focusing system.²³ In FEA, however, the angular spread of emitted electrons is up to 40° – 50° .³⁰ Although the electrons at extreme angles will not reach the target due to insufficient v_z , there could still be a substantial angular spread under typical operating conditions. The maximum θ_m of electron beam is $\sim 15^\circ$ when V_t and V_m are 20 and 300 V, respectively.² This indicates that the angular distribution is an important source for electron energy spread and lag in a FEA image sensor.

II.C. Beam acceptance characteristic curve

Because of the energy spread, the amount of electrons landing on the target (i.e., I_a) varies as target potential V_t changes. The amount of image charge read out during t_p is determined by the integral of I_a , which decreases as V_t

FIG. 4. Two hypothetical BACCs to illustrate their dependence on the energy spread of an electron beam. The corresponding energy distribution functions of the electrons are shown in the inset graph. A wider energy spread results in a shallower slope of the BACC.

gradually decreases during the readout process. To determine how much charge is left on the target after each readout, i.e., beam discharge lag, it is important to investigate the dependence of I_a on V_t , i.e., $I_a(V_t)$, which is called the beam acceptance characteristic curve (BACC). BACC provides information about the energy spread (specifically, the spread in the vertical kinetic energy component E_z) of the electron beam. Assuming E_{z0} is the lowest E_z with which the electron can reach the target at potential V_t , the BACC can be related to the energy spread $P_z(E_z)$ through

$$I_a(V_t) = \int_{E_{z0}}^{+\infty} P_z(E_z) dE_z, \quad (2)$$

which is the complementary cumulative distribution function of $P_z(E_z)$. Shown in Fig. 4 are two conceptual BACCs with their corresponding probability distribution functions for electron energy spread. Electron beams with wider energy spread would result in a shallower rising slope on the BACC. As V_t continues to increase, I_a reaches saturation when electrons with the lowest energy are able to reach the target.

BACC has been investigated extensively for camera tubes to quantify beam discharge lag.^{22,23} When the photocurrent in the target changes abruptly from I_{p1} to I_{p2} as a result of change in light exposure, the target potential changes accordingly by ΔV_t . However, the readout signal current, i.e., I_a , changes gradually following the relationship:^{24,31}

$$\Delta Q = C_t \Delta V_t = (I_{p2} - I_a(t)) \Delta t, \quad (3)$$

where C_t is the target capacitance. Equation (3) describes the relationship between the amount of charge (ΔQ) read out by the electron beam and the corresponding change in the target potential (ΔV_t) during a beam dwelling time interval (Δt). To describe how to derive lag using the BACC, we assume a starting equilibrium condition of $I_a = I_{p1}$ at time $t=0$, when the light exposure increases abruptly to I_{p2} . Image charge

begins to accumulate on the free surface, i.e., $\Delta Q > 0$, which causes V_t to increase. Based on the BACC, this leads to an increase in I_a until a new equilibrium is established with $I_a(t) = I_{p2}$. With a steep slope for the BACC, a small increase in V_t would result in a substantial increase in I_a , resulting in a rapid transition into the new equilibrium, i.e., small lag. Using Eq. (3) and the BACC the time dependence of signal, which quantifies lag, can be predicted.

III. METHODS

Theoretical and experimental methods were developed to understand the lag of FEA imaging sensors. Our theoretical method was to predict the energy spread of the electron beam and its associated BACC. From the BACC the lag for FEA image sensor with a given target structure and readout speed could be predicted. Then the predicted lag was compared with the experimental measurements from two prototype FEA image sensors with different HARP layer thicknesses.

III.A. Energy spread and BACC

All three factors contributing to the energy spread of an electron beam were investigated theoretically: (1) Inherent energy spread associated with field emission, (2) FEA driving pulse delay, and (3) angular distribution of emitted electrons. Here we will describe the method for each factor separately.

III.A.1. Inherent energy spread

The energy distribution of electrons from field emission has been investigated extensively.^{26,28,29} Theoretical³² and experimental^{33,34} studies have shown that the probability distribution of electrons emitted with inherent energy E_i is given by

$$P_i(E_i) dE_i = \frac{4\pi m d}{h^3} e^{(-c + [\phi/d])} e^{((E_i - \phi)/d)} (e^{(E_i/kT)} + 1)^{-1} dE_i, \quad (4)$$

where h is the Planck constant, k is the Boltzmann constant, Φ is the work function of the emitter material, and c and d are two functions related to the applied electric field E_{FE} .²⁷

As shown in Fig. 2, in order for an electron to reach the target with potential V_t , it needs to have an initial energy $E_i \geq q(V_b - V_t)$. Therefore the signal current $I_a(V_t)$ can be obtained by integrating the emitted electrons in this energy range:

$$I_a(V_t) = q A_e \int_{q(V_b - V_t)}^{\infty} P_i(E_i) dE_i, \quad (5)$$

where A_e is the effective emission area. Equation (5) provides the BACC associated with the inherent energy spread only.

III.A.2. Driving pulse delay

The driving pulse delay is mainly associated with the base electrode line, which contains the pixel clock. The time response of the driving pulse was simplified using a single exponential decay function:

$$V_b(t) = V_g \exp(-t/\tau), \quad (6)$$

where τ is the RC time constant for the total resistive and capacitive load for each line. An emitted electron accumulates a kinetic energy of $E_{bg} = q(V_g - V_b)$ when it passes through the gate electrode. Hence the probability of an electron possessing a kinetic energy of $E_{bg} = q(V_g - V_b)$ is proportional to the amount of electrons emitted at V_b :

$$P_b(E_{bg})dE_{bg} = N_b I_e(V_b)dt = N_b I_e(V_b) \frac{dt}{dE_{bg}} dE_{bg}, \quad (7)$$

where N_b is a normalization factor to ensure a total probability of unity. The emission current density $I_e(V_b)$ under different operation conditions can be obtained using the method described in Ref. 29. The values for dt/dE_{bg} can be obtained using the driving pulse delay expression in Eq. (6) and $E_{bg} = q(V_g - V_b)$. Equation (7) was solved numerically by dividing t_p into small time intervals dt (~ 0.1 nS) and calculating the value of $I_e(V_b)$ and dE_{bg} during each time interval. In order for an emitted electron to reach the target, its initial kinetic energy E_{bg} must be sufficient to overcome the potential difference between the gate electrode and the target, i.e., $E_{bg} \geq q(V_g - V_t)$. Hence the total beam current reaching the target with potential V_t can be obtained by

$$I_a(V_t) = \int_{q(V_g - V_t)}^{\infty} P_b(E_{bg})dE_{bg}. \quad (8)$$

Equation (8) can be used to derive a BACC that includes only the effect of variation in V_b due to driving pulse delay.

III.A.3. Angular distribution

For the present investigation, we used the angular distribution of electrons emitted from Spindt-type FEA for the calculation of energy spread. This type of FEA was incorporated in the HARP-FEA image sensors used in the experimental measurement of lag. It was also used as an example in our previous investigation of spatial resolution of SAPHIRE.² Here the same angular distribution adapted from Ref. 30 was used in our calculation.³⁰ Shown in Fig. 5 is the electron beam intensity as a function of emission angle (θ), i.e., $I(\theta)$.

For electrons with a kinetic energy of E_g at the gate electrode,⁷ their vertical components E_z can be calculated using $E_z = E_g \cos^2 \theta$. Its probability distribution can be derived (in the Appendix) as

$$P_z(E_z) = N_0 \frac{I(\theta)}{\cos \theta}, \quad (9)$$

where N_0 is a normalization factor. If E_z is greater than the potential difference between the target and the gate electrode

FIG. 5. Angular distribution of the intensity of emitted electron beams in Spindt-type field emitters, adapted from Ref. 30.

(V_g), i.e., $E_z > q(V_g - V_t)$, the electron can land on the target and contribute to I_a :

$$I_a(V_t) = \int_{q(V_g - V_t)}^{\infty} P_z(E_z)dE_z. \quad (10)$$

Equation (10) defines the BACC that only includes the energy spread due to the angular distribution of emitted electrons.

III.A.4. Total energy spread

The energy spread of electrons due to the first two factors, which are given in Eqs. (4) and (7), were first combined to provide the total energy E_g of an electron at the gate electrode:

$$E_g = E_i + E_{gb}. \quad (11)$$

The joint probability distribution for E_g is given by

$$P_g(E_g) = \sum_{E_i} P_i(E_i) \cdot P_b(E_g - E_i). \quad (12)$$

Equation (12) was then substituted with Eq. (9) to obtain the total energy (z -component) spread as $P_o(E_z)$:

$$P_o(E_z) = \sum_{E_g} P_g(E_g) \cdot \frac{I(\theta)}{\cos(\theta)}, \quad (13)$$

To obtain the BACC due to the total energy spread, Eq. (13) was substituted into Eq. (10):

$$I_a(V_t) = \int_{q(V_g - V_t)}^{\infty} P_o(E_z)dE_z. \quad (14)$$

III.B. Prediction of lag

When the photocurrent in the HARP target changes from I_{p1} to I_{p2} due to exposure change at time $t=0$, the beam discharge lag, $L(t)$, can be expressed as

$$L(t) = \frac{I_a(t) - I_{p2}}{I_{p1} - I_{p2}} \times 100\%. \quad (15)$$

When $I_{p1} > I_{p2}$, it is called turn-off lag or white-to-black lag; otherwise, it is called turn-on lag. The turn-on lag in electron beam readout is usually smaller than the turn-off lag due to the shape of the BACC;¹⁸ hence we will focus our study on the turn-off lag. To calculate $L(t)$, we need to obtain the time dependent signal current $I_a(t)$. As described in Sec. II C, the BACC and Eq. (3) can be used to solve $I_a(t)$ numerically by dividing t into small time intervals Δt ($\sim t_p/10^4$ in our calculation) and updating V_t and I_a in real time.

III.C. Experimental measurement of lag

The experimental measurement of lag was performed on two small-area HARP-FEA prototype optical image sensors with different HARP layer thicknesses.⁷ The geometry and structure of the prototype sensor were identical to those used in our previous investigation of the spatial resolution of SAPHIRE.² The FEA contains 256×192 pixels, with pixel size of $d_{el} = 50 \mu\text{m}$. The emitting area of $d_a = 20 \mu\text{m}$, which contains 17×17 Spindt-type FE tips, is located in the center of each pixel. The FEA was turned on pixel by pixel using a passive driving scheme with $t_p = 160 \text{ nS}$ and $V_g = 48 \text{ V}$. The HARP layer thicknesses in the two prototype sensors were $d_{se} = 4 \mu\text{m}$ and $25 \mu\text{m}$, with corresponding high voltage biases (applied to ITO electrode) of 440 and 2580 V, respectively.

IV. RESULTS AND DISCUSSIONS

IV.A. Beam discharge lag

IV.A.1. Inherent energy spread

The inherent energy distribution for electrons through field emission is given by Eq. (4). For Spindt-type FEA with Mo emitters that is operated at room temperature, $\Phi = 4.6 \text{ eV}$ and $T = 300 \text{ K}$. Typically E_{FE} needs to be $> 10^9 \text{ V/m}$ to maintain a reasonable field emission current.¹⁷ It was estimated that E_{FE} of $\sim 7 \times 10^9 \text{ V/m}$ was maintained with $V_g = 48 \text{ V}$ for the Spindt-type FEA in our prototype sensors. Figure 6(a) plots the inherent energy distributions at $V_g = 48 \text{ V}$ in comparison with $V_g = 40$ and 60 V . Their corresponding BACC were calculated using Eq. (5). Since both emission current and energy spread change as a function of V_g , the calculated BACCs were normalized, as shown in Fig. 6(b), to facilitate the comparison of energy spread, which is reflected by the slope of the curves.

Figure 6(a) shows that the maximum energy E_i of emitted electrons is $\sim -4.6 \text{ eV}$ for all three V_g . This is because the energy is defined relative to the vacuum level and the work function for Mo is $\Phi = 4.6 \text{ eV}$. At $T = 300 \text{ K}$, the energy for most electrons is below the Fermi level. Figure 6(a) also shows that the standard deviations, σ_i , of the inherent energy spread increases as E_{FE} increases. They are 0.26, 0.34, and 0.42 eV, respectively, for V_g values of 40, 48, and 60 V. This is because at higher V_g (i.e., higher E_{FE}), more electrons with lower E_i can emit through tunneling. The inherent energy

FIG. 6. (a) The inherent energy (E_i) distribution of emitted electrons at different V_g for Mo emitters at room temperature. (b) The BACCs associated with the inherent energy spread in (a) at different V_g .

spread is smaller than that in thermionic emission (used in electron tubes), which is typically 0.6–0.7 eV in theory.³² Figure 6(b) shows that a smaller V_g leads to a sharper rising slope but with smaller emission current.

IV.A.2. Driving pulse delay

The variation in base potential V_b due to driving pulse delay results in a variation in energy gain as the emitted electrons pass the gate electrode. The value for V_b was calculated using Eq. (6) with $\tau = 70 \text{ nS}$. The distribution of energy gain E_{bg} was calculated using Eq. (7) and the results are shown in Fig. 7(a) for a gate bias potential of $V_g = 48 \text{ V}$. The corresponding BACC was obtained using Eq. (8) and shown in Fig. 7(b).

Figure 7(a) shows that more electrons are emitted with higher E_{bg} (i.e., as V_b approaches 0 V). This is because a lower V_b results in higher E_{FE} and emission current. The

FIG. 7. (a) The distribution of energy accumulation (E_{bg}) of electrons due to the delay of driving pulses as they pass through the gate with $V_g = 48$ V and delay time constant $\tau = 70$ nS. (b) The BACC associated with the energy spread due to driving pulse delay shown in (a).

standard deviation of E_{bg} distribution, σ_b , was obtained using Eq. (7) as 2.61 eV, which is substantially larger than σ_t . Listed in Table I are the σ_b values calculated for different FEA operating conditions. Since V_g is usually selected to ensure sufficient emission current (e.g., 2 μ A per pixel) for a wide dynamic range, the preferred method for decreasing

TABLE I. Standard deviation of energy spread σ_b due to driving pulse delay under different conditions. (a) σ_b as a function of V_g at $\tau = 70$ nS and σ_b as a function of τ at $V_g = 48$ V.

V_g (V)	40	48	60
σ_b (eV)	1.96	2.61	3.69
τ (nS)	60	70	80
σ_b (eV)	2.54	2.61	2.65

FIG. 8. (a) The distribution of the vertical component of kinetic energy (E_z) due to the angular distribution of emitted electrons. The total kinetic energy accumulated by the electrons as they pass through the gate, E_g , was assumed to be constant. (b) The normalized BACCs associated with the E_z distributions in (a).

σ_b is to increase the ratio of t_p/τ . Figure 7(b) shows that with driving pulse delay, the slope of BACC becomes shallower, and the intercept with the horizontal axis also increases by ~ 5 V. This shift in BACC can be predicted from Eq. (6) using $V_b(t_p) = V_g \exp(-t_p/\tau) = 48 \exp(-160/70)$, which corresponds to the minimum value of V_b at the end of the driving pulse duration $t_p = 160$ ns.

IV.A.3. Angular distribution

The angular distribution of electron beam intensity in Fig. 5 was used to calculate the distribution of E_z using Eq. (9), and the results are shown in Fig. 8(a) for three values of E_g .

TABLE II. Standard deviation of energy spread σ_z due to angular distribution under different operating conditions.

E_g (eV)	40	48	60
σ_z (eV)	5.03	6.04	7.55

Their corresponding BACCs, calculated using Eq. (10), are shown in Fig. 8(b). To facilitate comparison all curves were normalized.

Figure 8(a) shows that the maximum E_z corresponds to its associated E_g value. The shape of E_z is consistent with that of the angular distribution curve in Fig. 5. The standard deviation of E_z spread, σ_z , increases as E_g increases, as shown in Table II. This is because E_z is proportional to E_g through $E_z = E_g \cos^2 \theta$. Figure 8(b) shows that a larger energy spread (e.g., $E_g = 60$ eV) leads to a shallower slope for the BACC.

IV.A.4. Total energy spread

To combine all factors, the distribution of E_g , $[P_g(E_g)]$ due to the first two factors, was calculated using Eq. (12) as the first step; then the total E_z distribution $P_o(E_z)$ was obtained using Eq. (13). The results for $P_g(E_g)$ and $P_o(E_z)$ are shown in Fig. 9(a). The FEA operating parameters used in the calculation were chosen based on the prototype FEA sensors, i.e., $V_g = 48$ V.

Figure 9(a) shows that the first two factors result in a combined energy spread of $\sigma_g = 2.65$ eV for E_g and a reduction in the maximum E_g to ~ 38 eV, as shown in Fig. 9(a). After inclusion of the angular distribution, the standard deviation for the total energy spread in E_z is $\sigma_z = 5.51$ eV. The corresponding BACC is given in Fig. 9(b), which shows that the BACC has an intercept of ~ 10 V with the horizontal axis (i.e., V_t) and the rise in I_a occurs over a V_t span of ~ 20 V. These results are consistent with the total energy spread in E_z shown in Fig. 9(a).

IV.B. Prediction of lag

The BACC in Fig. 9(b) was used to predict the beam discharge lag using Eqs. (3) and (15). All the calculation parameters were chosen based on the operating conditions of two prototype HARP-FEA sensors, where the emission current was $I_e = 2$ $\mu\text{A}/\text{pixel}$ at $V_g = 48$ V. The initial photocurrent was $I_{p1} = 200$ nA, i.e., the maximum signal current experienced by the prototype sensor. The thicknesses of the HARP target for the two prototype sensors were $d_{se} = 4$ and 25 μm . The final signal current I_{p2} was selected to be the dark current (i.e., no optical exposure), which is < 1 nA in avalanche mode. The calculated lag curves for both prototype sensors are shown in Fig. 10. Lag was normalized to the signal prior to the exposure change, as defined in Eq. (5). The first frame lags (at 33 ms or second field) are 60.3% and 9.2% for $d_{se} = 4$ and $d_{se} = 25$ μm , respectively.

IV.C. Measurement of lag

The turn-off lag was measured for both prototype HARP-FEA optical sensors using the method described in Sec.

FIG. 9. (a) The energy spread in E_g (dashed line) due to the first two factors and the total energy spread in E_z (solid line) due to all three factors at $V_g = 48$ V. (b) The BACC corresponding to the total energy spread in E_z due to all three factors at $V_g = 48$ V.

III C, and the results are plotted in Fig. 10 together with the theoretical calculations for both HARP layer thicknesses. The measured first frame lags were 62.1% and 9.1% for $d_{se} = 4$ μm and $d_{se} = 25$ μm , respectively. The lower lag for thicker HARP target is due to the smaller C_t under the same FEA operating conditions. The measurement and theoretical calculation are in excellent agreement.

IV.D. Strategies for lag reduction with FEA readout method

Our results showed that the measured lag agrees well with the theoretical calculation, which validates our understanding of the mechanisms. However, the amplitude of lag is much larger than that for electron tube devices. Methods for reducing lag are needed before FEA readout method can be used

FIG. 10. Comparison between calculated and measured lags as a function of frame number (at 30 frames/s) for two prototype HARP-FeA image sensors. The HARP layer thickness was $d_{\text{Se}}=4 \mu\text{m}$ and $25 \mu\text{m}$.

in practical imaging applications. Here we will discuss several strategies for reducing lag based on our understanding of its mechanisms.

IV.D.1. Reducing energy spread of electrons

To improve the spatial resolution of SAPHIRE, an electrostatic beam focusing method is being investigated.² The additional focusing electrode, which is built directly above each single FE tip using photolithography, will redirect the electrons emitted at large angles into the vertical direction. Therefore it has the potential to reduce the angular spread of emitted electrons, which is the dominant source of energy spread and lag. Once a FEA with focusing electrode is manufactured, the angular distribution of emitted electrons will be investigated and its corresponding change in E_z calculated to estimate the improvement in lag.

IV.D.2. Alternative driving schemes

One of the advantages of the FEA over the scanning electron beam is its array structure, which makes it possible to turn on multiple FEA pixels at the same time. A lag clearance procedure can be implemented between the readout of subsequent frames. At the end of each frame, all the FEA pixels will be turned on simultaneously for a lag clearance period t_c that is equal to the time required to reset the target potential V_t . For example, to reduce lag to 2% in a $25 \mu\text{m}$ thick HARP target, $t_c=3t_p$ is required according to Fig. 10. This method is equivalent to reading out the pixel for four consecutive frames although only the signal from the first frame is recorded. For image sensors with a large number of pixels, e.g., 1000×1000 , the total current needs to be drawn from the FEA driving circuit may be prohibitive. In this case, the clearance procedure can be implemented between subsequent rows or a number of rows.

FIG. 11. Schematic diagram showing the concept of dividing the ITO electrode into multiple strips to enable parallel beam readout. The rectangles depict the ITO stripes, and the squares depict the pixels. The shaded squares illustrate the pixels addressed simultaneously by the FEA.

IV.D.3. Lag reduction in SAPHIRE

With the lag clearance procedure described above, the lag of a small-area (2.54 cm diameter) HARP-FeA image sensor can be reduced to a negligible level. However, the size of SAPHIRE for x-ray imaging is much larger, and major changes are needed to allow real-time readout without lag. A $25 \times 20 \text{ cm}^2$ cardiac detector with $200 \mu\text{m}$ pixel size has 1250×1000 pixels and requires $t_p < 30 \text{ ns}$ with pixel-by-pixel readout in 30 frames/s. Lag with such short t_p would be unacceptable. Although the results in Fig. 10 suggest that thicker HARP layers could be used to reduce lag, there is a practical upper limit for the thickness of HARP, which is $35 \mu\text{m}$.⁸ In addition, thicker HARP requires higher bias potential, which increases the complexity of detector construction. Hence, a more practical method for reducing lag, i.e., parallel beam readout method, will be pursued for SAPHIRE.³⁵ The ITO electrode of SAPHIRE will be divided into N_s parallel strips, each connected to an individual charge amplifier, as shown in Fig. 11. In parallel beam readout, N_s pixels are turned on simultaneously, thus increasing t_p by a factor of N_s compared to the pixel-by-pixel approach. This in turn will minimize driving pulse delay for large-area FEA, which also helps reduce lag.

To illustrate quantitatively the effects of pixel size, detector size, and N_s on the lag of SAPHIRE, we provide an example of lag calculation for a hypothetical SAPHIRE with $d_{\text{Se}}=25 \mu\text{m}$, $d_{\text{el}}=200 \mu\text{m}$ and a detector size of $25 \times 20 \text{ cm}^2$. The signal current chosen for lag calculation, $I_{p1}=2 \mu\text{A}$, corresponds to the mean detector exposure of $1 \mu\text{R/frame}$ in fluoroscopy. For real-time applications with higher exposures (e.g., cine and angiography), the range of signal current is expected to be similar to that in fluoroscopy since the avalanche gain of HARP will be reduced.^{2,5} The operating condition for Spindt-type FEA is assumed to be $V_g=48 \text{ V}$. Compared to the optical HARP-FeA sensor with $50 \mu\text{m}$ pixel size discussed earlier, the pixel size of a SAPHIRE is 16 times larger, which increases both I_e and C_t

FIG. 12. The prediction of lag for SAPHIRE with and without parallel beam readout. The detector parameters used were $d_{sc}=25\ \mu\text{m}$, $I_{p1}=2\ \mu\text{A}$, $I_{p2}=0$, and $V_g=48\ \text{V}$.

by a factor of 16. According to Eq. (3), the lag for SAPHIRE should be independent of pixel size. The calculated lags with different N_s values are shown in Fig. 12. With $N_s=1$, t_p for SAPHIRE is $\sim 26\ \text{nS}$ with pixel-by-pixel readout. Even if we ignore driving pulse delay with such a short t_p , the first frame lag is 42%, which is unacceptable. With $N_s=16$ and parallel readout, t_p increases to 420 nS, and the first frame lag is reduced to 8%. With $N_s=128$ and further increase in t_p to $3.4\ \mu\text{S}$, the first frame lag is 4.3%, which is within the range of lag values measured in AMFPis.^{13–15} Further reduction in lag could be realized by incorporating the charge clearance procedure described in Sec. IV D 2. It is important to note that the lag calculation results in Fig. 12 only included the effects of the inherent energy spread and angular distribution, which resulted in underestimation of lag for $N_s < 40$ due to driving pulse delay. However, driving pulse delay is negligible in the preferred detector configuration of $N_s=128$.

V. CONCLUSION

A new detector concept SAPHIRE has been proposed. In this paper, we investigated its temporal performance. The beam discharge lag is the dominant lag source, which is due to the energy spread among electron beams. The mechanism of field emission electron beam on FEA is investigated by including three main factors: The inherent energy spread, the base potential delay effect, and the angular distribution effect. The dominant source of the energy spread is the angular distribution. Our prediction agrees very well with experiments on a small-area optical HARP-FEA sensor. Due to the large size of SAPHIRE, several methods are designed based on the mechanism of field emission to improve its temporal performance. Parallel beam readout can increase the pixel turn-on time and remove the base potential delay effect, as well as help reduce the beam discharge lag. With proper design, the lag of SAPHIRE is expected to be less than 5%

after the first frame. It can be optimized by a flushing method to remove the residual signals. Electrostatic focusing method has the potential reduce the angular distribution effect greatly.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support by the National Institutes of Health (Grant No. 1 R01 EB002655) and Army Breast Cancer Research Program (Grant No. W81XWH0410554). The authors thank their NHK colleagues M. Kubota and K. Miyagawa, for their help in the fabrication of HARP layers.

APPENDIX: ENERGY SPREAD DUE TO THE ANGULAR DISTRIBUTION OF EMITTED ELECTRONS

If we assume the same kinetic energy of qV_g for all the emitted electrons when they pass through the gate electrode,⁷ only the electrons with smaller emission angles (i.e., higher v_z) can reach the target. Therefore there exists a critical emission angle θ_C , within which all the emitted electrons can reach the target.⁷ The accepted electron beam current I_a can be obtained by integrating the emitted beam intensity up to θ_C :

$$I_a = N \int_0^{2\pi} \int_0^{\theta_C} I(\theta) \sin \theta d\theta d\varphi = 2\pi N \int_0^{\theta_C} I(\theta) \sin \theta d\theta, \quad (\text{A1})$$

where N is a normalization factor to ensure $I_a=I_e$ when all electrons are collected. We also have

$$I_a = \int_{qV_g \cos^2 \theta_C}^{qV_g} P_z(E_z) dE_z, \quad (\text{A2})$$

where $E_z=qV_g \cos^2 \theta$ is the axial (vertical) kinetic energy. Since $dE_z=-2qV_g \sin \theta \cos \theta d\theta$, Eqs. (A1) and (A2) can be combined to obtain

$$P(E_z) = N_0 \frac{I(\theta)}{\cos \theta}, \quad (\text{A3})$$

where $N_0=\pi N/qV_g$.

^{a)}Electronic mail: dli@mil.sunysb.edu

¹W. Zhao, D. Li, A. Reznik, B. Lui, D. C. Hunt, K. Tanioka, and J. A. Rowlands, "Indirect flat-panel detector with avalanche gain: Design and operation of the avalanche photoconductor," *Proc. SPIE* **5745**, 352–360 (2005).

²D. Li and W. Zhao, "SAPHIRE (scintillator avalanche photoconductor with high resolution emitter readout) for low dose x-ray imaging: Spatial resolution," *Med. Phys.* **35**, 3151–3161 (2008).

³G. Juska and K. Arlauskas, "Impact ionization and mobilities of charge-carriers at high electric-fields in amorphous selenium," *Phys. Status Solidi A* **59**, 389–393 (1980).

⁴K. Tsuji, Y. Takasaki, T. Hirai, J. Yamzaki, and K. Tanioka, "Avalanche phenomenon in amorphous selenium," *Optoelectron., Devices Technol.* **9**, 367–378 (1994).

⁵W. Zhao, D. Li, A. Reznik, B. J. M. Lui, D. C. Hunt, J. A. Rowlands, Y. Ohkawa, and K. Tanioka, "Indirect flat-panel detector with avalanche gain: Fundamental feasibility investigation for SHARP-AMFPI (scintillator HARP active matrix flat panel imager)," *Med. Phys.* **32**, 2954–2966 (2005).

- ⁶C. A. Spindt, "Microelectronic field ionizer and method of fabricating same," U.S. Patent No. 4,926,056 (1990).
- ⁷Y. Takiguchi, M. Nanba, K. Osada, T. Watabe, S. Okazaki, N. Egami, K. Tanioka, M. Tanaka, and S. Itoh, "256×192 pixel field emitter array image sensor with high-gain avalanche rushing amorphous photoconductor target," *J. Vac. Sci. Technol. B* **22**, 1390–1395 (2004).
- ⁸A. Reznik, W. Zhao, Y. Ohkawa, K. Tanioka, and J. A. Rowlands, "Applications of avalanche multiplication in amorphous selenium to flat panel detectors for medical applications," *J. Mater. Sci.: Mater. Electron.* **20**, S63–S67 (2009).
- ⁹W. Zhao, D. C. Hunt, K. Tanioka, and J. A. Rowlands, "Indirect flat-panel detector with avalanche gain," *Proc. SPIE* **5368**, 150–161 (2004).
- ¹⁰M. Kubota, T. Kato, S. Suzuki, H. Maruyama, K. Shidara, K. Tanioka, K. Sameshima, T. Makishima, K. Tsuji, T. Hirai, and T. Yoshida, "Ultrahigh-sensitivity new super-HARP camera," *IEEE Trans. Broadcast.* **42**, 251–258 (1996).
- ¹¹B. Zhao and W. Zhao, "Temporal performance of amorphous selenium mammography detectors," *Med. Phys.* **32**, 128–136 (2005).
- ¹²J. E. Gray, J. G. Stears, F. Lopez, and M. A. Wondrow, "Fluoroscopic imaging—Quantitation of image lag or smearing," *Radiology* **150**, 563–567 (1984).
- ¹³J. H. Siewerdsen and D. A. Jaffray, "A ghost story: Spatio-temporal response characteristics of an indirect-detection flat-panel imager," *Med. Phys.* **26**, 1624–1641 (1999).
- ¹⁴P. R. Granfors, R. Aufreht, G. E. Possin, B. W. Giambattista, Z. S. Huang, J. Liu, and B. Ma, "Performance of a 41×41 cm² amorphous silicon flat panel x-ray detector designed for angiographic and R&F imaging applications," *Med. Phys.* **30**, 2715–2726 (2003).
- ¹⁵D. C. Hunt, O. Tousignant, and J. A. Rowlands, "Evaluation of the imaging properties of an amorphous selenium-based flat panel detector for digital fluoroscopy," *Med. Phys.* **31**, 1166–1175 (2004).
- ¹⁶M. Overdick, T. Solf, and H.-A. Wischmann, "Temporal artifacts in flat dynamic x-ray detectors," *Proc. SPIE* **4320**, 47–58 (2001).
- ¹⁷I. Brodie and C. A. Spindt, "Vacuum microelectronics," *Adv. Electron. Electron Phys.* **83**, 1–106 (1992).
- ¹⁸R. Luhta and J. A. Rowlands, "Feasibility of a large area x-ray sensitive vidicon for medical fluoroscopy: Resolution and lag factors," *Med. Phys.* **24**, 621–631 (1997).
- ¹⁹A. Rose, in *Interscience Tracts on Physics and Astronomy, No. 19*, edited by R. E. Marshak (Interscience, New York, 1963).
- ²⁰W. Zhao and J. A. Rowlands, "X-ray imaging using amorphous selenium: Feasibility of a flat panel self-scanned detector for digital radiology," *Med. Phys.* **22**, 1595–1604 (1995).
- ²¹W. D. Park and K. Tanioka, "Avalanche-type high sensitive image pickup tube using an a-Se photoconductive target," *Jpn. J. Appl. Phys., Part 2* **42**, L209–L211 (2003).
- ²²B. Meltzer and P. L. Holmes, "Beam temperature, discharge lag and target biasing in some television pick-up tubes," *Br. J. Appl. Phys.* **9**, 139–143 (1958).
- ²³L. J. v. d. Polder, "Target-stabilization effects in television pick-up tubes," *Philips Res. Rep.* **22**, 178–207 (1967).
- ²⁴O. Yoshida and Y. Kiuchi, "Calculations of image lag in vidicon-type camera tubes. 1. Beam discharge lag and total image lag, including photoconductive lag," *Jpn. J. Appl. Phys.* **10**, 1203–1211 (1971).
- ²⁵N. Egami, M. Nanba, Y. Takiguchi, K. Miyakawa, T. Watabe, S. Okazaki, K. Osada, Y. Obara, M. Tanaka, and S. Itoh, "50×50 μm pixel magnetic focus field emitter array image sensor with high-gain avalanche rushing amorphous photoconductor target," *J. Vac. Sci. Technol. B* **23**, 2056–2062 (2005).
- ²⁶R. H. Fowler and L. Nordheim, "Electron emission in intense electric fields," *Proc. R. Soc. London, Ser. A* **119**, 173–181 (1928).
- ²⁷R. H. Good and E. W. Muller, "Field emission," *Handbuch der Physik (Springer-Verlag, Berlin, 1956)*, Vol. 21, pp. 176–231.
- ²⁸R. Gomer, in *American Vacuum Society Classics*, edited by H. F. Dylla (American Institute of Physics, New York, 1993).
- ²⁹G. Fursey, in *MICRODEVICES Physics and Fabrication Technologies*, edited by I. Brodie and P. Schwoebel (Kluwer Academic, Dordrecht/Plenum, New York, 2005).
- ³⁰S. Itoh, T. Watanabe, K. Ohtsu, M. Taniguchi, S. Uzawa, and N. Nishimura, "Experimental study of field-emission properties of the Spindt-type field emitter," *J. Vac. Sci. Technol. B* **13**, 487–490 (1995).
- ³¹J. M. Sandrik, in *Medical Physics Monograph No 11: Electronic Imaging in Medicine*, edited by G. D. Fullerton, W. R. Hendee, J. C. Lasher, W. S. Properzio, and S. J. Riederer (AIP, New York, 1984), pp. 145–183.
- ³²R. D. Young, "Theoretical total-energy distribution of field-emitted electrons," *Phys. Rev.* **113**, 110–114 (1959).
- ³³R. D. Young and E. W. Muller, "Experimental measurement of the total-energy distribution of field-emitted electrons," *Phys. Rev.* **113**, 115–120 (1959).
- ³⁴L. W. Swanson and L. C. Crouser, "Total-energy distribution of field-emitted electrons and single-plane work functions for tungsten," *Phys. Rev.* **163**, 622–641 (1967).
- ³⁵D. Li and W. Zhao, "SAPHIRE (Selenium Avalanche Photoconductor with High Resolution Emitter Readout): Investigation of Parallel Beam Readout," RSNA Annual Meeting, Chicago, 2007, p. 270.